

Near-infrared single-photon-counting detectors for free-space laser receivers

Michael A. Krainak, Xiaoli Sun, William Hasselbrack,
Stewart Wu, Augustyn Waczynski, Laddawan Miko

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract

We compare several photon-counting detector technologies for use as near-infrared time-resolved laser receivers in science instrument, communication and navigation systems. The key technologies are InGaAs(P) photocathode hybrid photomultiplier tubes and InGaAs(P) and HgCdTe avalanche photodiodes. We discuss recent experimental results and applications.

Introduction

Minimizing system mass, power, volume and cost are vital considerations for deploying systems in space. Optimum systems maximize individual component efficiency. This culminates at the fundamental physical limits. For laser technology this means maximizing the wall-plug efficiency. Recently, solid-state Yb:YAG lasers¹ and Yb and Er fiber lasers^{2,3} are providing a path for high-efficiency space-borne laser transmitters. For time-resolved laser systems⁴⁻⁷, maximizing system efficiency requires single-photon-counting detectors. These detectors enable laser receivers that have high sensitivity at the efficient-laser-compatible wavelengths - most notably 1.0 and 1.5 μm . In addition, laser spectroscopic instruments for important atmospheric trace-gas remote-sensing require gas-specific-wavelength sensitive detectors (e.g. carbon dioxide⁵ at 1.57 μm and methane⁶ at 3.3 μm). Our applications require large area (diameter > 170 μm) detectors at the receiver telescope focal plane.

Hybrid Photomultiplier Tube (HPMT)

Near-infrared hybrid photomultiplier tubes⁸ (HPMT) consist of a transfer electron (InGaAsP or InGaAs) photocathode and an electron bombarded GaAs Schottky avalanche diode anode separated by two electron optics focusing baffles. The device is 30mm in length and 30mm in diameter. Unlike Geiger mode InGaAsP APDs, these HPMTs (also known as intensified photodiode (IPD), vacuum APD, or hybrid photodetector) operate in linear mode without the need for quenching and gating. Their greatest advantages are wide dynamic range, high speed, large photosensitive area (1 mm), and potential for photon counting and analog detection dual-mode operation. The photon detection efficiency we measured was 25% at 1064 nm wavelength with a dark count rate of 60,000/s at -22 degrees Celsius. The output pulse width in response to a single photon detection is about 0.9 ns. The maximum count rate was 90 Mc/s and was limited solely by the speed of the discriminator used in the measurement (10 ns dead time). The spectral response of these devices extended from 900 to 1300 nm. The timing jitter of the HPMT output was found to be about 0.5 ns standard deviation and depended on bias voltage applied to the TE photocathode. We are in the process of testing a similar HPMT with a

smaller diameter (167 μm x 167 μm) InGaAs photocathode (1.55 μm wavelength) to reduce dark counts. The anticipated performance is >20% detection efficiency and <100kcps @ -20 C with 1 GHz bandwidth.

Avalanche photodiodes (APDs)

We conducted non-gated single photon counting measurements on InGaAsP/InP⁹ and InGaAs/InP APDs optimized for operation at 1.06 μm and 1.55 μm respectively. These devices were fabricated with a planar-passivated dopant-diffused (non-mesa) high reliability structure. Devices were characterized by measuring the total count rate as a function of photon flux for flux values in the range 10^{-1} to 10^8 photons per second. Beyond a count rate of $\sim 10^4 \text{ s}^{-1}$, signal counts exceed dark counts. Signal counts can be measured over three orders of magnitude before saturation is encountered. At a detection efficiency of 2%, 80 μm diameter devices were shown to exhibit free-running operation with dark count rates below 1000 Hz when operated at 230 K. Under these conditions, photon counting rates exceeding 1 MHz have been obtained. Significantly higher detection efficiencies (>30%) are achievable with acceptable tradeoffs in dark count rate. Initial characterization of afterpulsing effects in the 1.06 μm InGaAsP APDs shows that afterpulsing effects are very strong for hold-off times shorter than $\sim 1 \mu\text{s}$. To increase count rates beyond the range of 1 – 10 MHz, these afterpulsing characteristics will require improvements to allow for shorter hold-off times.

NASA has been developing HgCdTe imaging arrays following the success of the Hubble Space Telescope Wide Field Camera. We are now expanding the effort in HgCdTe APD arrays, not only for higher sensitivity but also for high-speed response for lidar applications. We are in the process of measuring the photon-sensitive performance of linear mode HgCdTe APDs followed by a high-bandwidth transimpedance amplifier. Low-bandwidth results¹⁰ have been recently reported.

- [1] E. P. Ostby, R. A. Ackerman, J. C. Huie and R. L. Gentilman *Proceedings of SPIE* vol. 6346, 63460V, (2007)
- [2] A. Croteau, C. Paré, H. Zheng, P. Laperle, and Y. Taillon *Proc. of SPIE* vol. 6101, 61010G, (2006)
- [3] P. Wysocki, T. Wood, A. Grant, D. Holcomb, K. Chang, M. Santo, L. Braun, G. Johnson *Optical Fiber Conference PDPI7* (2006).
- [4] J. B. Abshire, D. J. Harding, X. Sun, M. A. Krainak, A. A. Seas, P. W. Dabney *Conference on Lasers and Electro-Optics* (2007)
- [5] J. Burris, A. Andrews, H. Riris, M. Krainak, J. Abshire, X. Sun, W. Heaps *Second International Symposium on Recent Advances in Quantitative Remote Sensing, Torrent (Valencia), Spain* (2006).
- [6] Special Issue on Mars Laser Communications Demonstration *IEEE LEOS Newsletter* vol. 19, No. 5 (2005).
- [7] H. Riris, X. Sun, J. Abshire, G. Allan, M. Krainak, S. Li, S. Chen, E. Wilson and A. Yu *American Geophysical Union (AGU) 2006 Fall Meeting* (2006).
- [8] X. Sun, M. A. Krainak, W. E. Hasselbrack, R. A. La Rue *SPIE Europe Volume 6583A Photon Counting Applications* (2007)
- [9] M. A. Itzler, X. Jiang, R. Ben-Michael, K. Slomkowski, M. A. Krainak, S. Wu, X. Sun *Conference on Lasers and Electro-Optics* (2007)
- [10] J. Beck, M. Woodall, R. Scritchfield, M. Ohlson, L. Wood, P. Mitra, and J. Robinson *Proc. SPIE* 6542, 654217 (2007)